REPORT DOCUMENTATION PAGE

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10 July 2001	Annual Report 1 July 2000 - 30 June 2001

4. TITLE AND SUBTITLE

Adaptive Protocols for Mobile Wireless Networks

5. FUNDING NUMBERS

N00014-00-1-0565

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
Ballston Centre Tower One
800 N. Quincy Street
Arlington, VA 22217-5660

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Progress is reported on basic research in mobile wireless communication networks for tactical applications. Research results are presented on adaptive, energy-efficient, distributed protocols for mobile wireless networks that must operate effectively over unreliable communication links in highly dynamic environments. The dominant feature of the research is the exploitation of interactions among protocols to capitalize on the opportunities and overcome the impediments presented by the tactical communications environment. The interactions among protocols involve not only the exchange of information but also the active cooperation of different classes of protocols to accomplish the common objective of reliable, energy-efficient distribution of information. The research goals include establishing and taking maximum advantage of a strong coupling of the various protocol layers with such physical-layer functions as antenna array processing, receiver processing, modulation and demodulation, error-control coding, and decoding. The development of side information in physical-layer operations and its effective utilization in adaptive protocols are fundamental elements of the adaptive protocols in our research.

14. SUBJECT TERMS

tactical communication networks, adaptive protocols, spread-spectrum, broadband antennas

15. NUMBER OF PAGES

9

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Annual Progress Report

Title: Adaptive Protocols for Mobile Wireless Networks

Office of Naval Research Number: N00014-00-1-0565

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Abstract

Progress is reported on basic research in mobile wireless communication networks for tactical applications. Research results are presented on adaptive, energy-efficient, distributed protocols for mobile wireless networks that must operate effectively over unreliable communication links in highly dynamic environments. The dominant feature of the research is the exploitation of interactions among protocols to capitalize on the opportunities and overcome the impediments presented by the tactical communications environment. The interactions among protocols involve not only the exchange of information but also the active cooperation of different classes of protocols to accomplish the common objective of reliable, energy-efficient distribution of information. The research goals include establishing and taking maximum advantage of a strong coupling of the various protocol layers with such physical-layer functions as antenna array processing, receiver processing, modulation and demodulation, error-control coding, and decoding. The development of side information in physical-layer operations and its effective utilization in adaptive protocols are fundamental elements of the adaptive protocols in our research.

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Research Progress

Progress in antenna research during the current reporting period has been primarily in two areas: (1) design and realization of a very broadband, omnidirectional (in azimuth) loaded monopole driven through a matching network and (2) development of physically robust loads suitable for deployment in such a monopole. The inductor load values and positions on the monopole are determined by an optimizer which maximizes bandwidth while constraining gain to be greater than a prescribed minimum. Bandwidth ratios of 12:1 for measured VSWR less than 3.5 and calculated system gain greater than 4.5 dBi have been achieved. For the broadband antenna to be practical, the loads must be compatible with physical robustness yet not impossible to characterize by the integral equation solution method used in the optimization procedure. To address these seemingly contradictory requirements, methods are under development by means of which one can accurately determine the circuit behavior of loading coils housed in structurally robust shields.

Research results have been obtained for acquisition of direct-sequence spread-spectrum packet transmissions with radios using omnidirectional or switched, sectorized antennas in distributed packet radio networks. The performance of both serial and hybrid algorithms for noncoherent acquisition has been evaluated. The role of the AGC system in the acquisition performance was evaluated; a previously undiscovered link between the AGC behavior and the acquisition performance was revealed and shown to have a detrimental effect on the performance; and a method for selecting a robust acquisition threshold was developed to mitigate the undesirable effect. The effect of the direct sequence spread-spectrum chip waveform, the sample-timing error, and the delay-locked loop characteristics on acquisition performance was also investigated.

Improved random access MAC protocols have been developed that are specifically designed for half-duplex DS mobile radio networks. The protocols divide the available bandwidth into several channels, one of which is reserved for control messages. We have shown that the use of a short DS clear-to-receive signal from the source mitigates most collisions of packet acknowledgement messages. We have also developed a MAC overlay protocol that supports virtual circuit connection in conjunction with packet data. The performance of the protocol is highly dependent on the effectiveness of channel selection and virtual circuit detection algorithms. We have developed algorithms that perform well in a variety of channel conditions. We have also developed adaptive pacing algorithms, where pacing refers to the amount of time a radio must listen to the channel after performing various tasks, such as sending or receiving a packet. The adaptive algorithms adjust automatically to extreme changes in the network and outperform algorithms that do not adapt.

A new queueing-theory model has been developed for end-to-end data flow across a split connection between fixed-site host in a wide-area high-speed network and a mobile host in a wireless subnetwork. The model is used to obtain closed-form expressions for several key

performance parameters of the connection. We have shown that the model accurately characterizes the performance of a split connection employing TCP as the transport protocol between the fixed-site host and a gateway node and a wireless-network-oriented transport protocol between the gateway and the mobile node.

We have developed and evaluated energy-efficient adaptive protocols for mobile distributed spread-spectrum packet communication networks. Several research projects on adaptive transmission, adaptive routing, and adaptive forwarding protocols have been completed for frequency-hop (FH) spread-spectrum networks, and research has been initiated on DS spread-spectrum networks. The adaptive transmission protocol provides energy-efficient communications over time-varying links, and it helps preserve critical links during times of stress in the network. Preservation of links in a virtual circuit is particularly crucial to providing the required quality of service for certain types of traffic such as voice messages. Adaptive routing is required because of the time-varying topology and interference environment, and our new adaptive forwarding protocol is used to respond to changes that occur in the network between routing updates. These three protocols are designed to interact in a way that provides effective and energy-efficient responses to variations in the network topology and link conditions. All three protocols utilize side information that is extracted in the demodulation and decoding processes of the individual communication terminals. Results on the network throughput and energy efficiency that are achieved by the adaptive transmission, forwarding, and routing protocols have been obtained. These results are presented in several publications listed in this report.

We have demonstrated the advantages of incorporating an energy metric in addition to a link-quality metric into least-resistance routing. Not only is there a significant increase in the energy efficiency of the routing protocol, but the network throughput is also improved in certain situations by allowing a more judicious choice of some high-energy links when warranted by the network conditions. We have also developed a new adaptive-forwarding protocol that provides short-term response to changes in propagation conditions and network topology. The forwarding protocol operates in conjunction with adaptive routing and adaptive transmission by providing rapid, energy-efficient responses to changes in the network. The new adaptive forwarding protocol responds more quickly than is feasible for a routing protocol, and we expect it to permit a reduction in overhead traffic. We believe this latter advantage will result from our expectation that the use of the new adaptive forwarding protocol will permit less frequent transmission of routing control packets.

Research in coding over the past year includes investigation of the minimum weight of geometric codes, examining which of the generalized Reed-Muller codes are spanned by their minimum-weight vectors, and finding PD-sets for linear codes with large automorphism groups. Progress has been made on all these fronts: a new upper bound for the minimum weight of geometric codes has been found, and this bound is conjectured to give a formula for the minimum weight in the

general case. Complete information on which of the generalized Reed-Muller codes are spanned by their minimum vectors has been found, and new results on cyclic codes should show exactly which of a class of geometric codes will have PD-sets.

A new algorithm for decoding Reed-Solomon codes has been developed that uses fast Fourier transforms and computes the message symbols directly without finding either the error locations or error magnitudes. Compared with the Berlekamp-Massey algorithm, the new method has a about the same decoding time complexity but permits simpler structures for both hardware and software implementations of the decoder. We are also developing a new method for decoding Hermitian codes. The approach uses Grobner bases and can be viewed as a generalization of our method for decoding Reed-Solomon codes. Compared to previous methods, a major advantage of the new method is its capability for decoding with both errors and erasures without increasing decoding time significantly. The ability to decode received words with errors and erasures improves system performance greatly over errors-only decoding.

Additional results in error-control coding include the development of shorter nonbinary cyclic and shortened cyclic codes as alternatives to Reed-Solomon and Hermitian codes. New efficient algorithms have been developed for soft-decision decoding of nonbinary cyclic and shortened cyclic codes. We have also derived an efficient method for obtaining interpolation polynomials in Gao's new algorithm for decoding Reed-Solomon codes, and we have constructed new quaternary sequences with optimal crosscorrelation properties for QPSK direct-sequence (DS) spread spectrum.

We have developed a concatenated coding scheme that provides a significant performance improvement over traditional turbo codes in many situations. In particular, these codes have a much lower error floor than turbo codes. The codes are based on turbo and simple parity-check codes, and do not have a significantly higher decoding complexity than turbo codes alone. In addition, we have developed some new code-combining hybrid ARQ transmission techniques and unequal error protection schemes that take advantage of this concatenated code. We have also investigated the performance of adaptive transmission schemes with imperfect channel-quality estimates, particularly in the context of CDMA networks.

Personnel Supported

Faculty, Clemson University: Michael Pursley (PI), Carl Baum, Chalmers Butler, Shuhong Gao, Joseph Hammond, Jennifer Key, John Komo, Daniel Noneaker, Harlan Russell

Faculty, University of Florida: John Shea

Graduate Research Assistants, Clemson University: Fred Block, Kelle Lynn Clark, Peng Ding, Jason Ellenburg, Jeffrey Farr, Jirapha Limbupasiriporn, Thomas Macdonald (MURI fellow), Frank Pisano, Virginia Rodrigues, Shawn Rogers, ,Jennifer van der Horst, Jeffrey Wysocarski, David Zook

Graduate Research Assistants, University of Florida: Bryan Davis, Hanjo Kim

Undergraduate Research Assistants, Clemson University: Jawone Kennedy, Japeth Light, William McMahan, Asa Pease, Jessica Pursley, Thomas Royster, Mike Shettle

Faculty and Student Honors and Awards

Faculty Honors and Awards:
  Three IEEE Millennium Medals, 2000
  National Science Foundation CAREER Award, 2001
  Three Clemson University Board of Trustees Awards for Faculty Excellence, 2001
  Clemson University Alumni Award for Outstanding Achievement in Research, 2000
  Clemson University Alumni Award for Outstanding Achievement in Research, 2001
  Honorary Member, Golden Key National Honor Society, 2000
  IEEE Communications Society Distinguished Lecturer, 2001

Graduate Student Awards:
  AFCEA Fellowship, 2001
  Clemson College of Engineering and Science Outstanding Graduate Researcher, 2001
  Clemson University Outstanding Graduate Researcher, 2001

Undergraduate Student Awards:
  IEEE Region 3 Student Paper Competition, First Place, 2001

Publications Sponsored by this Grant:

Journal Publications:

K. L. Clark, J. D. Key, and M. J. de Resmini, "Dual codes of translation planes," submitted for publication in the *European Journal of Combinatorics*.

P. Ding and J. D. Key, "Minimum-weight codewords as generators of generalized Reed-Muller codes," *IEEE Transactions on Information Theory*, vol. 46, no. 6, pp. 2152-2158, September 2000.

P. Ding and J. D. Key, "Subcodes of projective generalized Reed-Muller codes spanned by minimum-weight vectors," accepted for publication in *Designs, Codes and Cryptography*.

S. Gao, "Abelian groups, Gauss periods, and normal bases," *Finite Fields and Their Applications*, vol. 7, pp. 149-164, January 2001.

S. Gao, "Factoring multivariate polynomials via partial differential equations," submitted for publication in the journal *Mathematics of Computation*.

S. Gao, E. Kaltofen, and A. G. B. Lauder, "Deterministic distinct degree factorization for polynomials over finite fields," submitted for publication in the *Journal of Symbolic Computation*.

S. Gao and A. G. B. Lauder, "Hensel lifting and bivariate polynomial factorisation over finite fields," accepted for publication in the journal *Mathematics of Computation*.

J. H. Gass, Jr., D. L. Noneaker, and M. B. Pursley, "A comparison of slow-frequency-hop and direct-sequence spread-spectrum communications over doubly selective fading channels," submitted for publication in the *IEEE Transactions on Communications*.

J. H. Gass, Jr., M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "An adaptive-transmission for frequency-hop wireless communication networks," accepted for publication in the journal *Wireless Networks*, vol. 7, no. 5, 2001.

L. L. Joiner and J. J. Komo, "Errors and erasures decoding of Reed-Solomon codes for M-ary orthogonal signaling," submitted for publication in the *IEEE Transactions on Communications*.

T. G. Macdonald and M. B. Pursley, "Staggered interleaving and iterative errors-and-erasures decoding for frequency-hop spread spectrum," submitted for publication in the *IEEE Journal on Selected Areas in Communications*.

D. L. Noneaker, A. R. Raghavan, and C. W. Baum, "The effect of automatic gain control on serial, matched-filter acquisition in direct-sequence packet radio communications," accepted for publication in the *IEEE Transactions on Vehicular Technology*.

F. A. Pisano III and C. M. Butler, "Analysis of a cylindrical antenna containing an aperture coupled load," accepted for publication in the *IEEE Transactions on Antennas and Propagation*.

F. A. Pisano III and C. M. Butler, "Methods for modeling wire antennas loaded with shielded networks," submitted for publication in *IEEE Transactions on Antennas and Propagation*.

S. D. Rogers, J. C. Young, and C. M. Butler, "Monopoles loaded with coils: a comparison of measured and computed results," accepted for publication in the *Journal of Electromagnetic Waves and Applications.*

S. D. Rogers, C. M. Butler, and A. Q. Martin, "Realization of a GA-optimized wire antenna with 5:1 bandwidth," accepted for publication in the journal *Radio Science.*

J. M. Shea, "Concatenated parity and turbo codes," submitted for publication in *IEE Electronics Letters.*

T. F. Wong and J. M. Shea, "Multi-dimensional parity-check codes for bursty channels," submitted for publication in the *IEEE Transactions on Information Theory.*

F. Xie, J. L. Hammond, and D. L. Noneaker, "Performance of a split-connection scheme for wireless internet access," submitted for publication in the journal *Wireless Networks.*

F. Xie, J. L. Hammond, and D. L. Noneaker, "Steady-state analysis of a split-connection scheme for mobile internet access," submitted for publication in the *IEEE/ACM Transactions on Networking.*

J. C. Young and C. M. Butler, "Inductance of a shielded coil," accepted for publication in the *IEEE Transactions on Antennas and Propagation.*

J. C. Young and C. M. Butler, "Inductance of a shielded coil with slots," accepted for publication in the *IEEE Transactions on Antennas and Propagation.*

Conference Publications:

R. T. Balaji and C. W. Baum, "A multimedia MAC protocol for distributed DS mobile radio networks," accepted for publication in the *Proceedings of the 2001 IEEE Military Communications Conference*, (McLean, VA), October 2001.

C. M. Butler, "Inductance of a practical shielded coil," accepted for publication in the *IEEE Antennas and Propagation Society International Symposium*, (Boston, MA), July 2001.

J. P. Coon, T. G. Macdonald, and M. B. Pursley, "A new method for obtaining side information in frequency-hop spread-spectrum systems," *Proceedings of the 2000 IEEE Military Communications Conference*, (Los Angeles, CA), vol. 1, pp. 5.2.1-5, October 2000.

S. Gao and A. G. B. Lauder, "Fast absolute irreducibility testing via Newton polytopes," submitted for publication in the *Fifth Asian Symposium on Computer Mathematics*, (Ehime University, Japan), September 2001, .

L. L. Joiner and J. J. Komo. "Nonbinary shortened cyclic codes," *Proceedings of the IEEE International Symposium on Information Theory and Applications* (Honolulu, HI), pp. 442-444, November 2000.

J. J. Komo, and L. L. Joiner. "QPSK maximal length sequences for spread spectrum multiple access," accepted for publication in the *Proceedings of the 2001 IEEE International Symposium on Information Theory*, (Washington, DC), June 2001.

L. L. Joiner and J. J. Komo. "Soft decision decoding of Reed-Solomon codes using the extended erasure magnitude matrix," *Proceedings of the 2000 IEEE Military Communications Conference* (Los Angeles, CA), vol. 1, pp. 12.3.1-5, October 2000.

T. G. Macdonald and M. B. Pursley, "Frequency-hop spread-spectrum packet radio with Hermitian codes," accepted for publication in the *Proceedings of the 2001 IEEE Military Communication Conference,* (McLean, VA), October 2001.

D. L. Noneaker, "Robust hybrid acquisition of DS packet transmissions," accepted for publication in the *Proceedings of the Sixth International Symposium on Communications Theory and Applications*, (Ambleside, UK), July 2001.

D. L. Noneaker, "The performance of serial, matched-filter acquisition in direct-sequence packet radio communications," accepted for publication in the *Proceedings of the 2001 IEEE Military Communications Conference* (McLean, VA), October 2001.

A. C. Pease and H. B. Russell, "Performance of the reliable all-informed voice networking (RAVEN) system in dynamic network topologies," *Proceedings of the 2001 IEEE Southeast Conference*, pp. 49-54, March 2001.

J. A. Pursley, "Turbo product codes and channel capacity," *IEEE Southeast Conference Student Paper Competition*, March 2001.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient routing in frequency-hop radio networks with partial-band interference," *Proceedings of the 2001 IEEE Wireless Communications and Networking Conference*, (Chicago, IL), vol. 1, pp. 79-83, September 2000.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Tradeoffs in the design of routing metrics for frequency-hop wireless networks," *Proceedings of the 2000 IEEE Military Communications Conference*, (Los Angeles, CA), vol. 1, pp. 3.1.1-5, October 2000.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "Energy-efficient protocols for mobile wireless spread-spectrum communication networks," accepted for publication in the *Proceedings of the Sixth International Symposium on Communication Theory and Applications*, (Ambleside, UK), July 2001.

M. B. Pursley, H. B. Russell, and J. S. Wysocarski, "An improved forwarding protocol for updating channel state information in mobile FH wireless networks," accepted for publication in the *Proceedings of the 2001 IEEE Military Communications Conference*, (McLean, VA), October 2001.

S. D. Rogers, C. M. Butler, and A. Q. Martin, "Genetic algorithm optimization and realization of broadband loaded wire monopoles," accepted for publication in the *IEEE Antennas and Propagation Society International Symposium*, (Boston, MA), July 2001.

J. M. Shea, "Adaptive signaling schemes with imperfect channel-quality estimates in wireless CDMA communications," *Proceedings of the 2000 IEEE Military Communications Conference,* (Los Angeles, CA), vol. 3, pp. 26.2.1-5, October 2000.

J. M. Shea, "Improving the performance of turbo codes through concatenation with rectangular parity check codes," accepted for publication in the *Proceedings of the 2001 IEEE International Symposium on Information Theory*, (Washington, DC), June 2001.

J. M. Shea and T. F. Wong, "Concatenated codes based on multidimensional parity-check codes and turbo codes," accepted for publication in the *Proceedings of the 2001 IEEE Military Communications Conference*, (McLean, VA), October 2001.

J. M. Shea and T. F. Wong, "Reduced-complexity decoding for concatenated codes based on rectangular parity-check codes and turbo codes," submitted for publication in the *Proceedings of the 2001 IEEE Global Communications Conference*, (San Antonio, TX), November 2001.

T. F. Wong and J. M. Shea, "Using multi-dimensional parity-check codes to obtain diversity in Rayleigh fading channels," submitted for publication in the *Proceedings of the 2001 IEEE Global Communications Conference*, (San Antonio, TX), November 2001.

T. F. Wong and J. M. Shea, "Multi-dimensional parity-check codes for bursty channels," accepted for publication in the *Proceedings of the 2001 IEEE International Symposium on Information Theory*, (Washington, DC), June 2001.

J. C. Young and C. M. Butler, "Analysis and design of shielded inductors," *Proceedings of the 2001 URSI-International Symposium on Electromagnetic Theory*, (Victoria, British Columbia), pp. 633-636, May 2001.